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ELECTRON BEAM APPLICATION TO WELDING
SPACE PROPULSION COMPONENTS

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ABSTRACT

Electron beam techniques for joining components of space engines have been employed at the Lewis Research Center of NASA for more than three years. Fabrication methods developed include the production of porous tungsten ion emitters, thermionic diode assemblies, and liquid metal heat transfer assemblies. Materials involved in these applications include tungsten, porous tungsten, molybdenum, tantalum, columbium 1% zirconium, columbium, titanium, and stainless steel. Some applications have involved the use of the electron beam for vaporizing metals onto nonmetals. Components produced for Zero G gravity testing required vaporizing tungsten and nichrome materials onto glass and ceramics.

Electron beam equipment employed includes both high and low voltage power sources.

Author

E-2547

ELECTRON BEAM APPLICATION TO WELDING SPACE PROPULSION COMPONENTS

The manufacture of space propulsion components has necessitated the use of very fine beam welding techniques. Many components of space engines require the joints be made under extremely clean conditions due to the nature of the materials involved. Initial attempts at making some of these joints with normal heliarc techniques were unsuccessful. The joint either had too wide a weld band, the large heated area caused cracking, or the joints became contaminated. In view of this, consideration was given to the possibility of solving these metals joining problems by the application of electron beam techniques.

Electron beam welding of space engine components at Lewis Research Center has been in use for more than three years. A high voltage welder was installed in December, 1960. Journeymen model-makers were selected to operate the equipment. Due to their thorough experience in fixturing and knowledge of metal movement and heat transfer, satisfactory welds were produced within a few weeks after the equipment was installed.

One of the first fabrication problems solved by the electron beam welder was the manufacture of ion engine emitters. Propulsion engines for space travel involve the use of an emitter that causes a metallic vapor, such as mercury or cesium, to ionize when it contacts the emitter surface. When a potential difference is impressed between the emitter surface and accelerator plates, the ionized metallic vapor is pulled from the emitter surface with a certain velocity. This ionized beam is the thrust developed for space propulsion. The emitter itself must have a good capacity, or work function, for ionizing the vapors, and it must have a maximum surface area for the greatest amount of ionization. A material that satisfies these requirements is porous tungsten. In an ion engine assembly, the porous tungsten emitter must be joined to a supporting structure. The supporting structure is usually wrought tungsten. The first design (fig. 1) involved installing a 0.060- by 0.300- by 6-inch-long porous tungsten into a wrought tungsten window of overall dimensions 1 1/2 by 8 inches long. Every attempt at making these welds resulted in cracking of the base materials. These joints were finally made by dividing the wrought tungsten into four pieces and putting each one on the porous tungsten individually. In this manner, the problem of attaching in the center of a wrought tungsten mass with its shrinkage problem, was overcome.

The second joint to be made was the attachment of a tantalum housing to the wrought tungsten supporting plate. This was performed by a titanium filler fusing the tungsten to the tantalum housing.

This design of emitter and housing involved a large amount of heat input before the porous tungsten would reach its operating temperature of 2350° F. A new design was suggested to reduce the necessary heat input. Instead of a tungsten window, it was suggested that a wrought tungsten channel be formed that would then be attached to the porous tungsten. (See figs. 2 and 3.) Two 6-inch long longitudinal seams were required. End pieces of wrought tungsten were then attached to the porous tungsten and wrought tungsten channel. A hole was then disintegrated into one end piece, and a tantalum tube attached. A columbium or titanium ring was first fitted over the tantalum tube, and the electron beam was focused on the filler ring. While the ring was melting, the adjacent areas of tungsten and tantalum got just hot enough to cause fusion in a brazing action with the use of the beam. This technique of brazing with the electron beam was used to give a crack-free joint. In this particular instance, a weld of the tantalum tube to the tungsten end plate was unsatisfactory. The weld alloy formed was brittle and, in some instances, showed cracks.

This design was used as a single emitter engine in most cases. In one assembly, an array of 10 emitters were constructed in one engine connected to the cesium boilers by tantalum and stainless-steel tubing.

The most recent emitter constructed with the electron beam welder has eliminated the need of a channel. The porous tungsten was purchased in the form of a tube. With the aid of beam deflection, all of the porous tungsten surface was washed by the beam to give an impervious surface, (fig. 4). Only a narrow strip of the porous surface was not washed and remained porous. End pieces were then welded to the porous tungsten tube, and a tantalum feed tube was brazed into the end piece with titanium or columbium.

Making ion emitters with porous tungsten tubes provided increased strength to the assembly, plus the advantage of heating by resistance means rather than by reflection.

Electron beam methods have proven very satisfactory in welding thin tungsten reflector shields and cylinders down to 0.0015 inches in thickness. The methods used required high table welding speeds up to 100 inches per minute. In some instances, the material was lapped, and the beam was pulsed to form the initial seam. Pulsation techniques minimize the shrinkage and lower the cracking tendency for the recrystallized tungsten weld. Butt welds are also made on 0.002-inch tungsten sheet. In this case, a high speed (up to 100 in./min.) is very advantageous in obtaining a crack-free weld.

Research efforts in extruding various materials have required the encapsulation of powders inside molybdenum and tungsten billets. The billets were installed in the vacuum chamber with the billet lid held open by a solenoid control. A heater around the billet raised the temperature to 400° F, while the vacuum system evacuated the system to a level of 1×10^{-5} Torr. After 12 hours of evacuation, the lid is closed on the billet with the solenoid control. The weld was then made between the lid and the tungsten billet. The heater was then turned off and the billet allowed to cool. When at room temperature, the billet was removed. In this manner, powders, both metallic and nonmetallic, are encapsulated in molybdenum and tungsten billets under highly evacuated conditions.

Some applications of electron beam equipment have necessitated the use of the beam as a heat source for vaporizing metals onto nonmetals, such as pyrex, boron nitride, and alumina. The materials vaporized were, in most cases, molybdenum and tungsten. Films of tungsten are used for small heater purposes in spacecraft application.

Tungsten tubes are also required to have a weld seam, which essentially has no crown or underbead. When attempting a straight butt joint of the tube, a crown or underbead would always result, regardless of the variations in beam intensity or table speed; however, the use of a tungsten filler strip minimized this effect. Beam welding in a vacuum allows the filler strip to heat at a faster rate than the butted tube ends. The result is the parent metal has minimum fusion, and somewhat of a brazing action results. This technique is used also for joining sandwich structures. Sintered metals and nonmetals are sheathed with tungsten. These sandwiches must then be joined. The use of a filler strip in electron beam welding these sandwich structures minimizes the amount of deterioration of the central, or core, material. Filler strip variations include the use of "T" sections. "T" sections were used as filler strips to prevent blow-thru of the top tungsten sheath. The total mass of the "T" section filler is then assimilated in the joint area.

One application for electron beam welding necessitated the construction of a liquid metals heater from 250 feet of columbium-1% zirconium. The manufacture of this heater posed a number of fabrication problems. (See fig. 5.) The material, 0.050-inch wall by 1-inch I.D. columbium-1% zirconium tubing was selected because of its compatibility with liquid metals and its relatively high strength at elevated temperature. The heater coil designed for 500-kilowatt operation was approximately 6 feet long, 18 inches deep, and 4 feet high.

Requirements in producing the heaters were that the weld material impurity level must not be on a higher level than the impurity level of the parent metal itself. The parent material also must not be contaminated by the processing operations. Incomplete penetration of parent metal by welds was unacceptable. Underbead was to be held to a minimum, undercut was completely unacceptable, and the weld metal had to be completely free of inclusions. Previous research efforts indicated the need to overage the welds at 2200° F. This was a precautionary measure against loss of ductility and corrosion resistance that might occur from precipitation of zirconium gas complexes in the grain boundaries of the weld metal.

In addition to all of these welding requirements, the tubing had to be chemically clean at all times.

The tubing provided, as previously stated, had a 1-inch I.D. and 0.050-inch wall, and the lengths varied between 17 and 19.5 feet. After some initial consideration was given to welding this heater by inert arc methods, it was finally decided to perform this operation by electron beam welding techniques. The equipment used was a 30,000-volt, 250-milliampere machine. The chamber on this unit is approximately 84 inches long, 36 inches deep, and 66 inches high. The chamber is evacuated by two 20-inch diffusion pumps and backed up by two 300-cubic-feet-per-minute mechanical roughing pumps. This vacuum pump system was capable of evacuating the chamber down to 1×10^{-6} Torr in 1 hour. An outgassing rate was observed at 1 micron increased in 1 hour, when clean procedures were observed in the chamber.

In fabricating the heater in this chamber, a decision had to be made in method of welding. Obviously, since the heater would be completed as one single length of tubing over 200 feet long fabricated from 19-foot lengths, the tubing would have to protrude through both ends of the welding chamber; however, the question arose whether the tubing should be rotated, or should the welding apparatus be rotated.

It was agreed to attempt to attain good welds by rotating the welding apparatus.

A table was available with the electron beam welding equipment, which allowed rotation of the electron gun in the horizontal plane. This table was revised to allow the gun to revolve in the vertical plane. The tubing would now pass through one port in the chamber, through the center of the welding table set vertically, and then through the port in the opposite end of the welding chamber. Necessary fixturing was provided at the welding area to allow close abutment of the tubes to be joined. In addition to slipping the tube through the welding fixture and chamber ports, a heater coil was also wrapped around the tubing in the far end of the chamber, away from the welding apparatus. The heater coil was used for overaging the welds at 2200° F.

Initial attempts at making a good weld with the gun rotating around the tube were very discouraging. The high voltage had to pass from the power leads to stationary power rails on the welding table. (See fig. 6.) The power rails were mounted on nylon supports. Brass shoes then picked up the power and fed the high voltage supply into the gun. Serious arcing was observed on the insulating supports on this apparatus. The shoes had to be remachined and the supports cleaned. Finally, with adequate shielding from the products vaporized by electron beam, the table remained clean and welding commenced.

Short lengths of tubing were initially used in the chamber to evaluate the fixturing. When these welds showed good penetration and quality, full length tubes were inserted through the ports. It was decided that no attempt would be made to evacuate to a high vacuum the

I.D. of the heater as it grew in length. A baffle was inserted inside the tube about 3 feet from the weld area. In this manner, only one length of tubing required evacuation of the I.D., regardless of the length of the tubing in the coil. Therefore, on the side of the heater where the loops were formed, only a rough pumpdown was held. (See fig. 5.) On the side where the extra tube was added, a diffusion pump and roughing pump held the I.D. of the tube to a pressure of 1×10^{-5} Torr and an outgassing rate down to 1-micron increase in 1 hour. The outgassing rate was only obtained by a system of high purity argon purges with subsequent preheat of the tubing and pumpdown.

With this evacuation technique, the first weld was made, then X-rayed and cut out for analysis. The analysis indicated no contamination of the weld. Subsequently, another weld was made, then heat treated at 2200° F, cut out, and analyzed. Once again, no contamination of the weld metal was observed by the processing techniques.

The next weld was then processed with X-ray inspection, heat treated, and the two tube length was bent up to the loop dimensions. New lengths of tubing were then added until 14 welds were made and a coil over 200 feet long was formed. In obtaining 14 good welds, two bad welds were cut out and the tubing rewelded. The bad welds were rejected because of arc-over of the welding apparatus, causing blow-through on the tubing. This condition was eliminated by cleaning the electron gun.

The applications discussed comprise essentially 90 percent of the work necessitating electron beam welding. In most instances, these applications involve the use of refractory metals. Occasionally, electron beam techniques are used involving other than refractory materials. Attaching of metallic auxiliary equipment to glass, metal, and ceramic-metal apparatus at times require the electron beam to keep the heat-affected area down to a minimum to prevent the loss of glass components from heat shock. Other applications require bead penetration through a stainless-steel sheath into strain gage apparatus supports. In these cases, the requirements for high depth-to-width ratios in the weld beads are extremely important to prevent overheating of fine wire circuits in the strain gage. The electron beam method is most suitable in applications of this type.

Another area of interest is the attachment of metals to nonmetals such as alumina and zirconia refractories. Success in performing these operations have been limited to small diameter tubes and wire attachment to the ceramics. In all cases, very limited results were obtained when the beam was directed on the ceramic-metal joint area. Best results were obtained when it was possible to direct all of the beam on the metal and allow conduction of heat from the metal to the ceramic to cause fusion of the joint area.

Experience has indicated that fixturing, along with knowledge of material characteristics, account for 80 percent of the effort required to obtain a satisfactory product. The advantages gained by welding in a vacuum with a high energy density electron beam are counterbalanced by the high degree of accuracy required in setting up parts to be welded. Generally, a part is joined by normal heliarc methods, unless the requirements for cleanliness and small heat-affected areas call for the electron beam methods. Electron beam joining is noted on prints. The machinists then are aware that their tolerances are much closer for joint preparations.

In preparing joints, usually an attempt is made to avoid focusing the beam in the center of the metal mass. When the beam is focused in the center, the contraction that occurs upon solidification sets up very high stresses. In the case where the material has a brittle recrystallization, as tungsten, cracking occurs to relieve the stress. One way to eliminate cracking is to design the joint to prevent melting in the center of a mass. Trepanning the parts is one way to accomplish this. (See figs. 7 and 8.)

Size consideration is also of the utmost importance. When attempting dissimilar material joints, it is usually worthwhile to place the more highly expansive material on the I.D. and the less expansive material on the O.D., when dealing with refractory materials. Less cracking of joints is observed with this technique. Some dissimilar combinations tend to form brittle intermetallics, even though the parent materials are basically ductile. Welding molybdenum to tantalum usually results in a brittle joint. The addition of titanium as a filler improves the ductility and gives a crack-free joint. The weld metal formed would, of course, have a somewhat lower melting point and would have to be compatible to the application.

Another method used at the Lewis Research Center is circle operation in the electron beam. Many applications require a large number of tubes to enter into a header plate. One application requires 34 ceramic feed-thru connectors to be attached to a stainless-steel plate. The connectors have 3/8-inch-diameter nickel-iron tubes attached to the ceramics by metallizing. The other end of the nickel-iron tube must be attached to the stainless-steel plates. Attempting to put 34 of these tubes into a 3-inch-diameter stainless-steel plate is an almost impossible task with normal electron beam techniques. Circle generation of the beam, however, simplifies this task. The 34 tubes are fitted to the stainless plate in a revolving chuck fixture with the stainless plate horizontal. The tubes are then programmed and spotted over the electron beam generated circle. In this manner, 34 welds are made, tube to header, in only one pumpdown of the chamber.

Many applications require extremely good evacuation techniques prior to welding. In these cases, the part to be welded is fitted up with a heater to preheat the apparatus to approximately 350° F. The chamber is baked out with radiation heaters, and argon purges of the chamber are conducted to obtain pressures of 1×10^{-6} Torr, and a chamber blankoff increase in pressure of less than 1 micron in 1 hour.

Generally, in accomplishing a task by the electron beam welder, 80 percent of the task is considered accomplished prior to the part being inserted in the weld chamber prior to welding. The close tolerances needed on joint preparation and material knowledge has required the use of personnel who are well acquainted with fixturing, machining, and model making. When attempting joints for space engine components, the success or failure of the assembly depends to a great extent on how well the welding personnel understand materials and on metal movement when heat is applied. At the Lewis Research Center, the welding personnel are selected from instrument model-making personnel. They understand the intricies of jigging and fixturing and understand metal movement, tolerances required, and heat effects when the beam is applied. Since they are basically instrument men, they can handle equipment maintenance, vacuum system control, and to a certain extent, trouble-shoot the electronic circuits.

Electron beam welding at Lewis has in the past accomplished many previously impossible joining problems. The future for electron beam techniques in joining space propulsion components is definitely showing signs of increased application.

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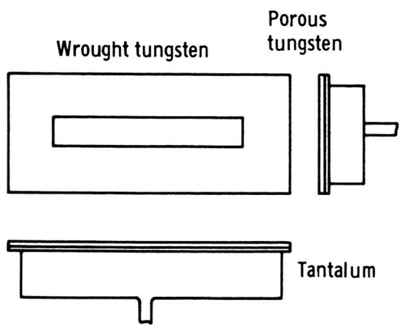

Figure 1. - Plate and box ion emitter.

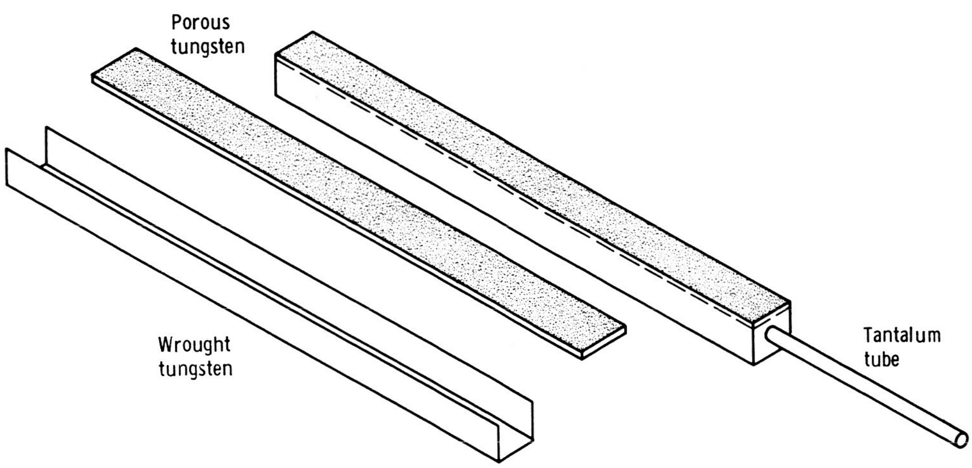

Figure 2. - Ion emitter assembly.

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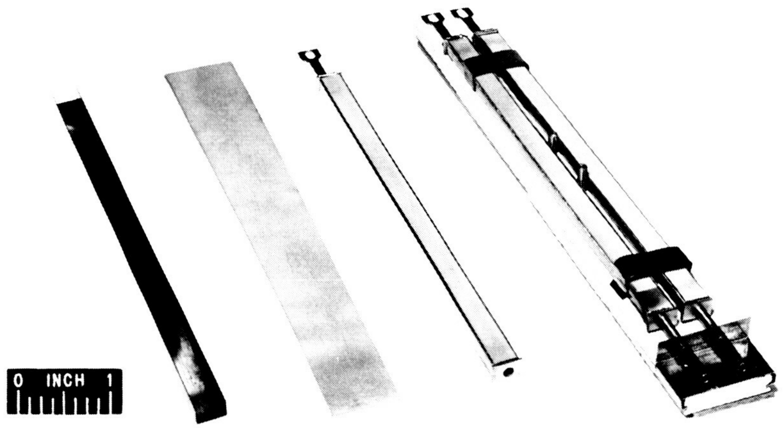

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Figure 3. - Ion engine emitter assembly.

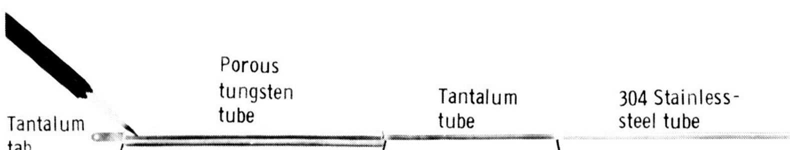

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Figure 4. - Porous tungsten ion engine emitter assembly.

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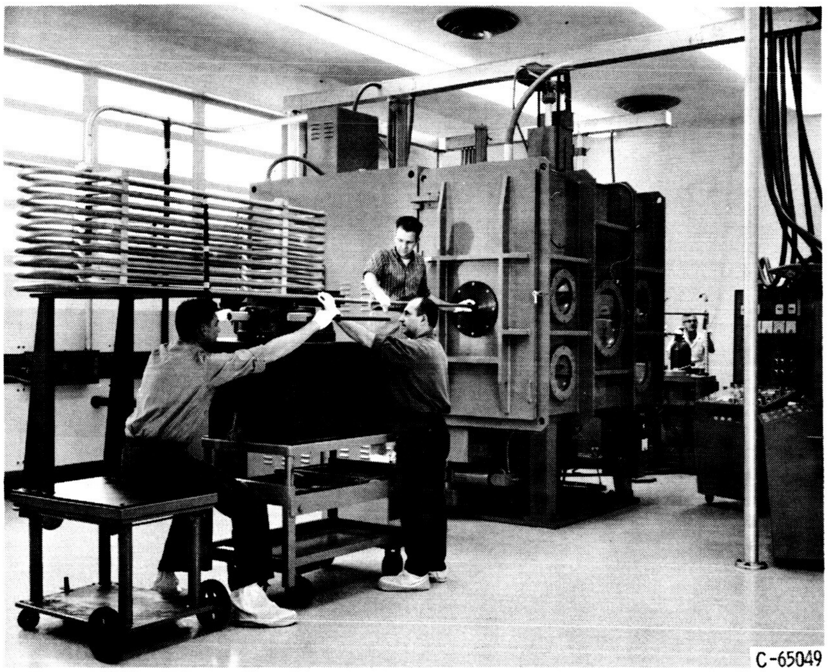

Figure 5. - Columbium - l-percent zirconium heater manufacturing operation.

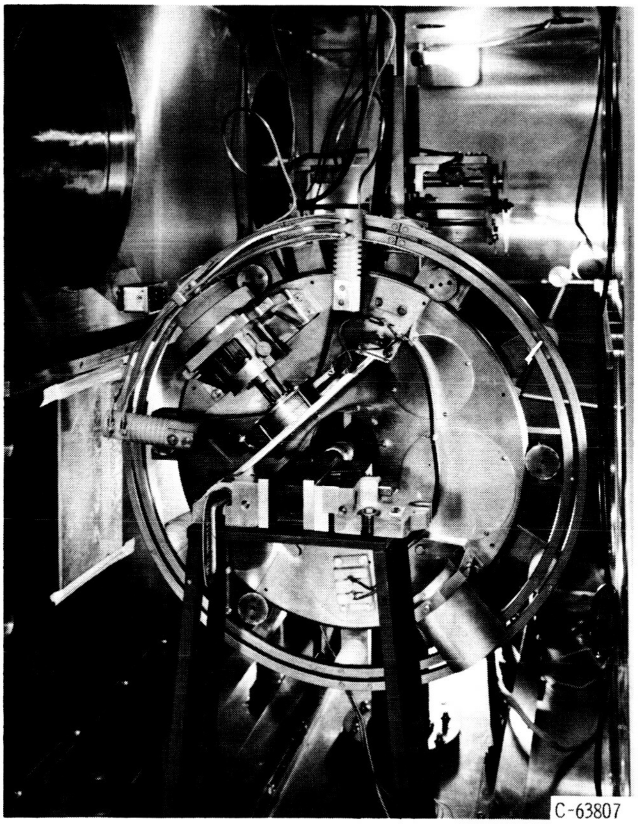

Figure 6. - Fixture for welding 1-inch I. D. columbium - 1-percent zirconium tubing.

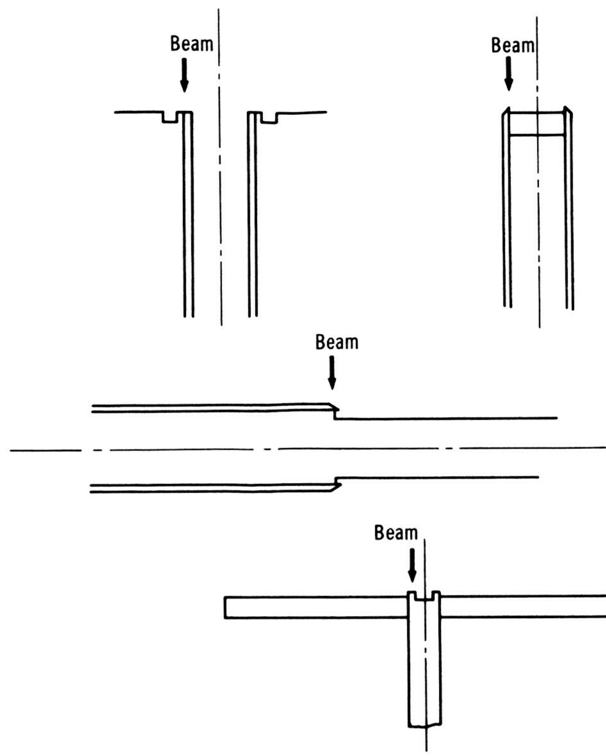

Figure 7. - Joint preparation for welding.

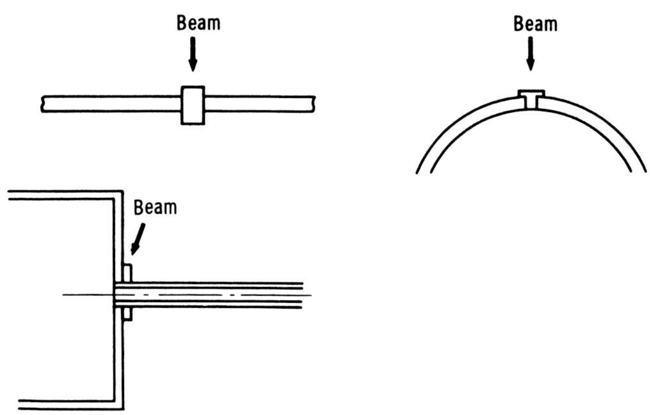

Figure 8. - Welding with fillers preplaced.

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